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(71) Applicant: STMicroelectronics Limited
Edinburgh EH12 7BF (GB)

(72) Inventor: Raynor, Jeff
Edinburgh EH12 7BF (GB)

(74) Representative: Cooper, John et al
Murgitroyd & Company
165-169 Scotland Street
Glasgow G5 8PL (GB)

(54) Solid state image sensors and microlens arrays

(57) A solid state image sensor comprises an array of pixels and a corresponding array of microlenses. The positions of the microlenses relative to their corresponding pixels vary according to the distances of the pixels from a central optical axis of the image sensor, so as to substantially eliminate vignetting of light collected by the microlenses. The array of microlenses is divided into blocks each comprising a plurality of microlenses. Within a particular block of microlenses, the positions of the microlenses relative to their corresponding pixels are varied by an equal amount. The microlenses within each of said blocks may be substantially equally spaced apart by a first distance and adjacent blocks of microlenses may be spaced apart by a second distance which is less than said first distance. Alternatively, the microlenses may be substantially equally spaced throughout said array of microlenses and selected microlenses at the edges of said blocks may be made smaller in at least one direction than the remainder of the microlenses of said blocks. The blocks may be rectangular or may have irregular edges configured such that said blocks are tessellated to form a substantially continuous array of microlenses. The pixel array and the light sensitive parts of the individual pixels preferably have substantially equal aspect ratios.

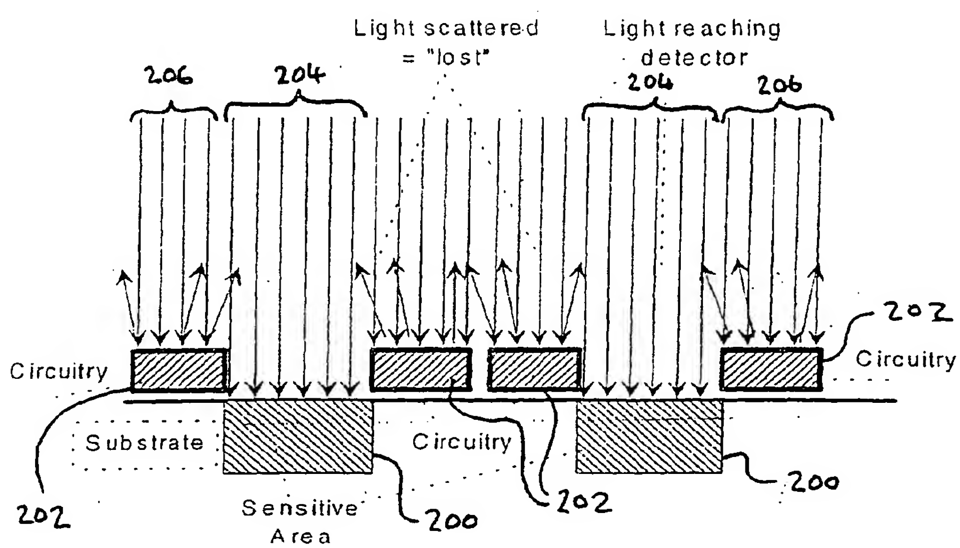

Figure 1 Pixel's circuitry obscures sensitive area

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Description

[0001] The present invention relates to solid state image sensors of the type comprising an array of light sensitive elements ("pixels") and more particularly to solid state image sensors employing an array of microlenses disposed in front of the pixel array.

[0002] A conventional solid state image sensor comprises an array of light sensitive pixels. Not all of the area of each pixel is light sensitive. In a CMOS type image sensor, typically about 50% of the area of each pixel is occupied by opaque, non-sensitive circuitry. Light impinging on the non-sensitive pixel area is not collected, resulting in a loss of sensitivity and degraded performance. This is illustrated schematically in Figure 1, which shows two adjacent pixels of a sensor array, each comprising a sensitive area 200 surrounded by non-sensitive circuitry 202. Light 204 which strikes the sensitive areas 200 contributes to the sensor output signal. Light 206 which strikes the non-sensitive circuitry 20 is scattered and "lost".

[0003] Such loss of sensitivity can be compensated for by the use of microlenses. As illustrated in Figure 2, a microlens 208 is associated with each pixel. The microlens 208 covers both the sensitive and non-sensitive areas 200 and 202 of the pixel, collecting light from most of the total pixel area and focussing the collected light onto the sensitive area 200 of the pixel. Accordingly, a greater proportion of the light striking the pixel area is collected and hence the sensitivity of each pixel is improved.

Typically, the use of microlenses approximately doubles the sensitivity of an equivalent sensor without microlenses.

[0004] This technique is well known in the art, as disclosed, for example, in US-A-4861140, US-A-5677200, US-A-5250798 and US-A-5614590.

[0005] The arrangement shown in Figure 2 is a simplification, showing only light rays which are perpendicular to the sensor surface so that the microlenses focus the light rays onto the centre of the sensitive area 200 of each pixel. This is true at the optical axis of the image sensor but, for pixels located off-axis, the light rays are non-perpendicular to the sensor surface, as shown in Figure 3. Here, because the light rays are non-perpendicular, the area onto which the light rays are focussed is shifted away from the centre of the sensitive area 200, but is still entirely within the sensitive area. The size of the shift is dependent on the curvature and refractive index (i.e. the focal length) of the microlens 208, the distance between the microlens and the sensor surface, the primary optics of the imaging system of which the sensor forms a part, and the distance of the pixel from the optical axis.

[0006] As long as the light collected by the microlens 208 is focussed entirely within the sensitive area 200 of the pixel, the shift of the focussing spot is not significant. However, if the shift is so extreme that the focussing spot is shifted partly or wholly out of the sensitive pixel area 200, as shown in Figure 4, the pixel will fail to detect some or all of the light, resulting in a loss of sensitivity known as "vignetting". This is a particular problem with CMOS type image sensors, which include a greater number of metal layers than, for example, CCD devices, so that there is a larger distance between the microlens and the sensor surface, which increases the shift of the focussing spot. One solution to this problem is to increase the exit pupil of the primary lens system, but this is expensive and not cost-effective for CMOS sensors which are generally used in low-cost imaging systems.

[0007] An alternative solution to the problem of vignetting is disclosed in US-A-5610390, in which the position of the microlens relative to the pixel is adjusted by an amount which varies with the distance of the pixel from the optical axis of the sensor array. This is illustrated in Figure 5, where the microlenses are shifted to the left by a distance d, as compared with Figure 4, so that the focussing spots are shifted back into the sensitive areas 200 of the pixels. According to US-A-5610390, the optical axis of each microlens is displaced towards the central axis of the sensor array by an amount which is proportional to the distance between the pixel and the central axis.

[0008] In theory, for a given sensor, microlens array and primary lens system, the spacing between adjacent microlenses may be adjusted, and hence their positions varied relative to the pixel array, in an optimal manner such that all of the light collected by each microlens is focussed on the centre of the associated pixel. However, an optimal solution would require different microlens arrays to suit the parameters of specific imaging systems. Also, the relative microlens shifts required for adjacent pixels are so small that it is impractical to apply the necessary displacements to individual microlenses in the manner disclosed in US-A-5610390.

[0009] It is an object of the present invention to provide an improved image sensor having a microlens array which obviates or mitigates the aforesaid disadvantages of the prior art.

[0010] In accordance with a first aspect of the invention, there is provided a solid state image sensor comprising an array of pixels and a corresponding array of microlenses disposed in front of said array of pixels, in which the positions of said microlenses relative to their corresponding pixels vary according to the distances of the pixels from a central optical axis of the image sensor, so as to substantially eliminate vignetting of light collected by the microlenses, wherein said array of microlenses is divided into blocks, each of said blocks comprising a plurality of microlenses, and wherein, within a particular block of microlenses, the positions of said microlenses relative to their corresponding pixels are varied by an equal amount.

[0011] In certain embodiments of the invention, the microlenses within each of said blocks are substantially equally spaced apart by a first distance and adjacent

blocks of microlenses are spaced apart by a second distance which is less than said first distance.

[0012] In other embodiments of the invention, the microlenses are substantially equally spaced throughout said array of microlenses and selected microlenses at the edges of said blocks are smaller in at least one direction than the remainder of the microlenses of said blocks.

[0013] In some embodiments of the invention, said blocks are substantially rectangular.

[0014] In other embodiments of the invention, said blocks have irregular edges configured such that said blocks are tessellated to form a substantially continuous array of microlenses.

[0015] In accordance with a second aspect of the invention, there is provided a solid state image sensor comprising an array of pixels, said array of pixels having a first aspect ratio and each of said pixels including a light-sensitive area having a second aspect ratio, wherein said first aspect ratio is substantially equal to said first aspect ratio.

[0016] In accordance with a third aspect of the invention, there is provided an imaging system including a solid state image sensor in accordance with the first or second aspects of the invention.

[0017] In accordance with a fourth aspect of the invention, there is provided a camera including a solid state image sensor in accordance with the first or second aspects of the invention.

[0018] Embodiments of the invention will now be described, by way of example only, with reference to the accompanying drawings, in which:

Figure 1 illustrates the structure of a pixel array of a conventional solid state image sensor;

Figure 2 illustrates a microlens array applied to the pixel array of Figure 1;

Figure 3 illustrates off-axis illumination of the pixel array of Figure 2;

Figure 4 illustrates extreme off-axis illumination of the pixel array of Figure 2, resulting in vignetting;

Figure 5 illustrates the displacement of microlenses relative to associated pixels to compensate for off-axis illumination;

Figure 6 is a schematic representation of the geometry of an image sensor with a microlens array and a primary lens;

Figures 7 and 8 illustrate individual pixels and displacements of microlenses and focussed light spots relative thereto;

Figure 9 illustrates a first embodiment of part of a microlens array in accordance with the present invention;

Figure 10 illustrates a second embodiment of part of a microlens array in accordance with the present invention;

Figure 11 illustrates the difference between a rectangular block of microlenses and a castellated block of microlenses as employed in embodiments of the present invention;

Figure 12 illustrates a third embodiment of part of a microlens array in accordance with the present invention, employing castellated blocks of microlenses;

Figure 13 illustrates a fourth embodiment of part of a microlens array in accordance with the present invention, employing castellated blocks of microlenses; and

Figure 14 illustrates the difference between a rectangular block of microlenses and a modified block of microlenses as employed in embodiments of the present invention.

[0019] Referring now to the drawings, Figure 6 illustrates an imaging system comprising a solid state image sensor 10 having a length/width D, a microlens array 12 having a thickness t and a refractive index n, and primary lens system 14 having a focal length f_B. For a pixel at the edge of the sensor 10, the focussing spot is shifted away from the centre of the sensor as a result of off-axis illumination by an amount s, where:

$$s = D \times t/(2 \times f_b \times n) \qquad (1)$$

[0020] The corresponding microlens would have to be shifted by the same amount in the opposite direction to compensate for this. Equation (1) is simplified for a one-dimensional (linear) sensor array, but is easily extended to two dimensions for a rectangular sensor array.

[0021] It will be understood that the present analysis is applicable to a range of types of primary lens systems including single- and multi- element lenses.

[0022] Figure 7 illustrates the corresponding situation for a pixel 16 and microlens 18 located at the top left hand corner of a two-dimensional sensor array. The microlens 18 is shifted towards the centre of the array in both the x and y directions, the x and y components s_x and s_y each being calculated by means of equation (1), using D_x and D_y for the x and y dimensions of the array. The shift of the microlens 18 relative to the pixel 16 results in the focussed light spot 22 falling in the centre of the sensitive area 20.

[0023] Equation (1) depends on the focal length of a specific primary lens system. This is disadvantageous since it means that the modified microlens array is matched to a particular primary focal length, restricting the range of different lenses that will work with the sensor without vignetting. It is desirable for a single sensor design to work with as large a range of primary lenses as possible. In order to maximise the range of possible primary lenses, it is important to note that the focussed light spot 22 does not need to fall in the centre of the sensitive area 20 in order to avoid vignetting. It is only necessary that substantially all of the focussed light falls somewhere within the sensitive area.

[0024] This is illustrated in Figure 8, which shows two focussed light spots 22a and 22b, as might be produced using two different primary lenses having different focal lengths. Both of the light spots 22a and 22b are within the sensitive area 20 of the pixel 16. Accordingly, it can be seen that a microlens position optimised for a given primary focal length will also be acceptable for a range of primary focal lengths. By way of example, one of the primary lenses is a telecentric lens (i.e. $f_B = \infty$) and the other has a shorter focal length $f_B = f_{B2}$. When the telecentric lens is used, light is perpendicular to the image plane and so the focussed light spot is directly beneath the centre of the lens (i.e. the shift s from equation (1) is equal to zero). If the microlens centre 24 is positioned above the centre of the light spot 22a at the most extreme acceptable position towards the central axis of the sensor (i.e. the lower right of the pixel sensitive area in this example where we are considering the top left pixel of the sensor array) then light from a telecentric lens will be focussed at that position and the focussed light spot for any shorter focal length will be shifted upwards and to the left. The shortest acceptable focal length will be that which produces the focussed light spot 22b at position 26, and can be calculated as follows:

$$s_{x1} = A_x/2 - d/2 \qquad \text{equation (2.1)}$$

$$s_{y1} = A_y/2 - d/2 \qquad \text{equation (2.2)}$$

where s_{x1} and s_{y1} are the required shifts in the x and y directions from the centre of the sensitive area 20 to the position 24, A_x is the width of the sensitive area 20, A_y is the height of the sensitive area 20 and d is the diameter of the focussed light spot.

[0025] By symmetry:

$$s_{x2} = A_x - d \qquad \text{equation (3.1)}$$

$$s_{y2} = A_y - d \qquad \text{equation (3.2)}$$

where s_{x2} and s_{y2} are the x and y shifts from position 24 to position 26.

[0026] From equation (1):

$$s_{x2} = D_x \times t/(2 \times f_{B2x} \times n) \qquad (4.1)$$

$$s_{y2} = D_y \times t/(2 \times f_{B2y} \times n) \qquad (4.2)$$

[0027] From equations (3) and (4):

$$f_{B2x} = D_x \times t/ (2 \times (A_x - d) \times n) \qquad (5.1)$$

$$f_{B2y} = Dy \times t/ (2 \times (A_y - d) \times n) \qquad (5.2)$$

[0028] Hence, considering the x-axis, the sensor can be used with lenses with a range of back focal length between ∞ and f_{B2x} without any vignetting in the x-axis. The range in the y-axis will be determined by f_{B2y}. Since a lens has only one focal length, the range will be limited by whichever axis vignettes first. Optimally, $f_{B2x} = f_{B2y}$, hence:

$$D_x \times t/(2 \times (A_x - d) \times n) = D_y \times t/(2 \times (A_y - d) \times n)$$

which can be simplified to:

$$D_x/A_x = D_y/A_y \qquad (6)$$

and rearranged to:

$$A_x/A_y = D_x/D_y \qquad (7)$$

[0029] From this analysis it follows that, for operation over a maximal range of lens focal lengths, the aspect ratio of the pixel's light sensitive area should be substantially equal to the aspect ratio of the image array as a whole. For example, if the image array has a 16:9 aspect ratio, the sensitive area of the pixel should also have a 16:9 aspect ratio in order to maximise the range of lenses that will operate with the microlenses and not cause vignetting.

[0030] As can be seen from equation (1), the shifts required to provide optimal placement of each microlens is proportional to the distance of each pixel from the centre of the image sensor (i.e. from the optical axis of the primary lens system), requiring a smooth, continuous shift of the centre positions of the microlenses as disclosed in US-A-5610390. Typically, the difference in shift between neighbouring pixels would be of the order of 10 nm - 15 nm. This is difficult or impossible to achieve

in practice, since the maximum design resolution (i.e. the minimum "snap-grid delta") for semiconductor masks employed in the manufacture of image sensors and microlens arrays is of the order of 50 nm - 100 nm.

[0031] In accordance with the present invention, the microlens array is divided into blocks, each comprising a plurality of microlenses, and variations in the parameters of the microlens array are applied to blocks of microlenses rather than to individual microlenses. This allows shifting of the microlenses to be accomplished without any modification of standard design or manufacturing technologies. The invention can be applied at the design stage, with no need to modify manufacturing processes, and is therefore easily implemented for high volume production.

[0032] For practical purposes, the minimum displacement which can be applied to a block of microlenses is equal to the minimum snap-grid delta, determined by the process technology as mentioned above (typically 50 - 100 nm). This dimension is referred to hereinafter simply as Delta and is smaller than the pixel size or feature size. The frequency of the displacement (i.e. the block size) may be selected such that the cumulative effect of the displacements produce the required shift of the microlenses.

[0033] This approach may be implemented in two basic ways:

(a) by varying the gap between adjacent blocks of microlenses, as illustrated in Figure 9;

(b) by varying the sizes of microlenses at selected edges of blocks, as illustrated in Figure 10.

[0034] Referring firstly to Figure 9, an array of microlenses is illustrated which is divided into four blocks. The lenses belonging to each of the four blocks are identified as A, B, C, D. The spacing between each microlens within each block is g1, which is greater than Delta. The spacing at the boundaries between each adjacent block is g2, where g2 is less than g1. If the optical axis of the array is at the intersection of blocks A, B, C and D, it will be seen that the effect of the reduced gaps g2 is to shift the optical axis of each of the individual microlenses within each block towards the optical axis of the array. If this shift is repeated for additional blocks surrounding the central blocks A, B, C, D, it will be seen that the cumulative shift will increase for blocks at increasing distances from the optical axis of the array.

[0035] The advantage of this implementation, in which the gap g2 between adjacent blocks is narrowed compared with the gap g1 between individual microlenses within a block, is that the microlenses are of constant size, providing constant optical performance and making the block boundaries less visible. The disadvantage is that the minimum size of g2 is determined by the process technology, so that g1 must always be greater than the minimum possible gap (the minimum possible gap size g1 = g2 + Delta), reducing the "fill-factor" of the microlenses and hence degrading sensor performance by reducing sensitivity.

[0036] Referring now to Figure 10, the alternative is for the gaps between individual microlenses and blocks of microlenses to be kept constant (usually at the minimum possible value), and to reduce the sizes of those microlenses at the block boundaries so that the blocks as a whole are effectively shifted in a manner similar to those of Figure 9. As shown in Figure 10, the "normal" microlenses have a size m1 x m1 whilst the reduced size microlenses have a size m2 x m1 or m2 x m2. The minimum difference between m1 and m2 is again determined by the design/process Delta value:

$$m1 = m2 + Delta.$$

[0037] The advantage of this implementation is that the gap size between all microlenses may be maintained at a minimum, maximising the fill-factor and sensitivity. The disadvantage is that the reduced size of the microlenses at the block boundaries, reducing the sensitivity of the corresponding pixels and possibly giving rise to visible patterning in the sensor output. Such patterning can be removed by calibrating the sensor using a white image and scaling the pixel outputs appropriately, or by disguising the edges in a manner to be described below.

[0038] In each case, the value of Delta is determined by the design system and/or process technology in use. The total microlens shift required at the corners of the sensor can be calculated as described above. It then remains to determine the size of the block (number of pixels) which will provide the required shift at the corners, which can be calculated (for each axis x and y) as follows:

$$\text{Block Size} = \text{INT}\,(\text{Delta} \times \text{NPix} / (2 \times s)) \qquad (8)$$

where:

Block Size =	number of rows/columns of pixels in block
Delta =	change in size (of gap or microlens)
NPix =	number of rows/columns of pixels in array
s =	microlens shift required at corners of array.

[0039] The INT (integer) function is required since only a whole number of pixels can be shifted.

[0040] For a typical image sensor array, the block size is likely to be in the range of about 4 to 10 rows/columns.

[0041] In both of the cases of Figures 9 and 10, the

cumulative effect of the block shifts is to shift individual microlenses so that substantially all of the light collected by each microlens is focussed within the sensitive area of the associated pixel. However, both arrangements create discontinuities in the spatial sensitivity response of the sensor array due to changes in the effective fill factor of the microlenses at the boundaries of the blocks.

[0042] A high performance digital still camera would typically go through a calibration stage during manufacture, in which the black level offset and gain of each pixel would be measured and stored in the camera to compensate for non-uniformities caused by manufacture of the image sensor. This technique would also substantially eliminate the effect of the sensitivity changes at the block boundaries of a microlens array in accordance with the present invention. However, this type of calibration adds significantly to the cost of the camera as it requires time and effort during manufacture and also requires the camera to include memory devices to store the correction parameters. Accordingly, this technique is too expensive to use in low cost imaging systems.

[0043] In accordance with a preferred feature of the invention, visible patterning arising from the discontinuities at the block boundaries may be disguised by the following methods, without adding to the cost of the sensor.

[0044] As described above in relation to Figures 9 and 10, the microlens array is divided into regular rectangular blocks, so that the boundaries comprise straight lines, causing visible patterning in the sensor output which is particularly apparent and objectionable. The boundaries may be disguised and the resultant patterning made less apparent by modifying the shapes of the blocks so that their boundaries are irregular.

[0045] Figure 11 illustrates an example of this idea applied to a 4x4 block of microlenses (it will be understood that the technique is applicable to blocks of any size). A regular, rectangular block 30 is shown, alongside a modified block 32 in which individual microlenses have effectively been displaced so that the edges of the block are "castellated". The total number of microlenses in the block remains the same, and a plurality of such modified blocks can be tessellated to form a continuous, uniform array.

This technique can be applied both in the case where block shifts are effected by narrowing the gaps between blocks (Figure 12) and in the case where block shifts are effected by reducing the size of microlenses at the block boundaries (Figure 13).

[0046] In Figures 12 and 13, the individual microlenses making up four blocks are again identified as A, B, C and D.

[0047] It will be understood that the size and shape of irregular blocks making up an array may vary from the illustrated examples, as long as the blocks are capable of being tessellated; i.e. they can fit together to form a substantially uniform, continuous array. Suitable designs of block shapes can easily be achieved by staring with a rectangular block and moving a block from one side to the other, as illustrated in Figure 14 which shows a rectangular block 34 and a corresponding block with one microlens moved. The same movement can be applied to microlenses on more than one side of the starting block, as illustrated by the example of Figure 11.

[0048] The present invention embraces solid state image sensors incorporating microlens arrays of the types described above and into imaging systems and cameras including such sensors.

[0049] Improvements and modifications may be incorporated without departing from the scope of the invention.

Claims

1. A solid state image sensor comprising an array of pixels and a corresponding array of microlenses disposed in front of said array of pixels, in which the positions of said microlenses relative to their corresponding pixels vary according to the distances of the pixels from a central optical axis of the image sensor, so as to substantially eliminate vignetting of light collected by the microlenses, wherein said array of microlenses is divided into blocks, each of said blocks comprising a plurality of microlenses, and wherein, within a particular block of microlenses, the positions of said microlenses relative to their corresponding pixels are varied by an equal amount.

2. A solid state image sensor as claimed in claim 1, wherein the microlenses within each of said blocks are substantially equally spaced apart by a first distance and wherein adjacent blocks of microlenses are spaced apart by a second distance which is less than said first distance.

3. A solid state image sensor as claimed in claim 1, wherein the microlenses are substantially equally spaced throughout said array of microlenses and wherein selected microlenses at the edges of said blocks are smaller in at least one direction than the remainder of the microlenses of said blocks.

4. A solid state image sensor as claimed in any one of claims 1 to 3, wherein said blocks are substantially rectangular.

5. A solid state image sensor as claimed in any one of claims 1 to 3, wherein said blocks have irregular edges configured such that said blocks are tessellated to form a substantially continuous array of microlenses.

6. A solid state image sensor comprising an array of pixels, said array of pixels having a first aspect ratio

and each of said pixels including a light-sensitive area having a second aspect ratio, wherein said first aspect ratio is substantially equal to said first aspect ratio.

7. A solid state image sensor as claimed in claim 6, further including a corresponding array of micro-lenses disposed in front of said array of pixels.

8. A solid state image sensor as claimed in any one of claims 1 to 5 in combination with claim 6 or claim 7.

9. An imaging system including a solid state image sensor as claimed in any one of claims 1 to 8.

10. A camera including a solid state image sensor as claimed in any one of claims 1 to 8.

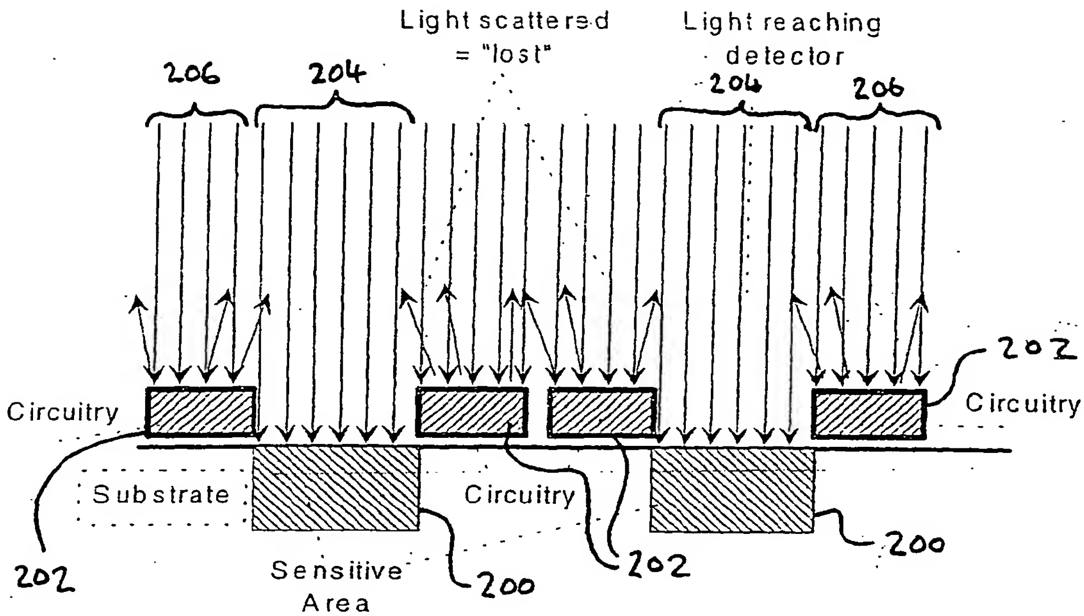

Figure 1 Pixel's circuitry obscures sensitive area

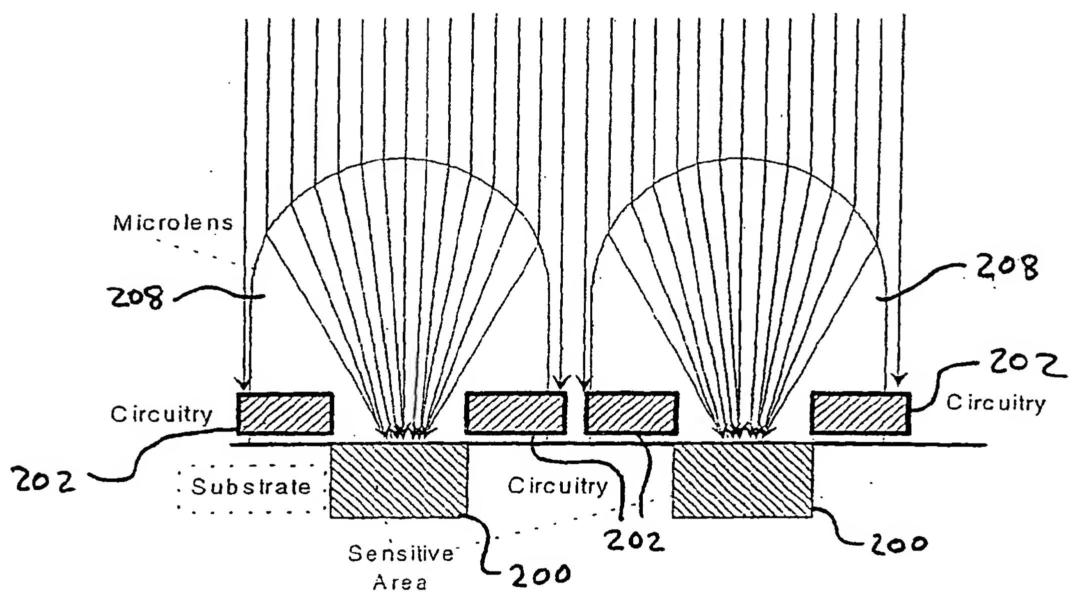

Figure 2 Microlens focuses most of the light on sensitive area

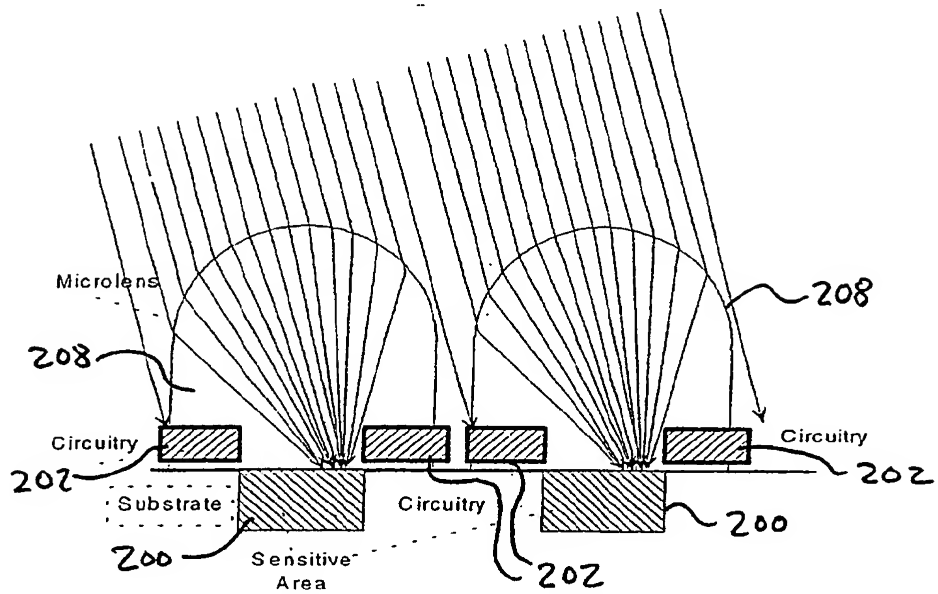

Figure 3 Off axis illumination

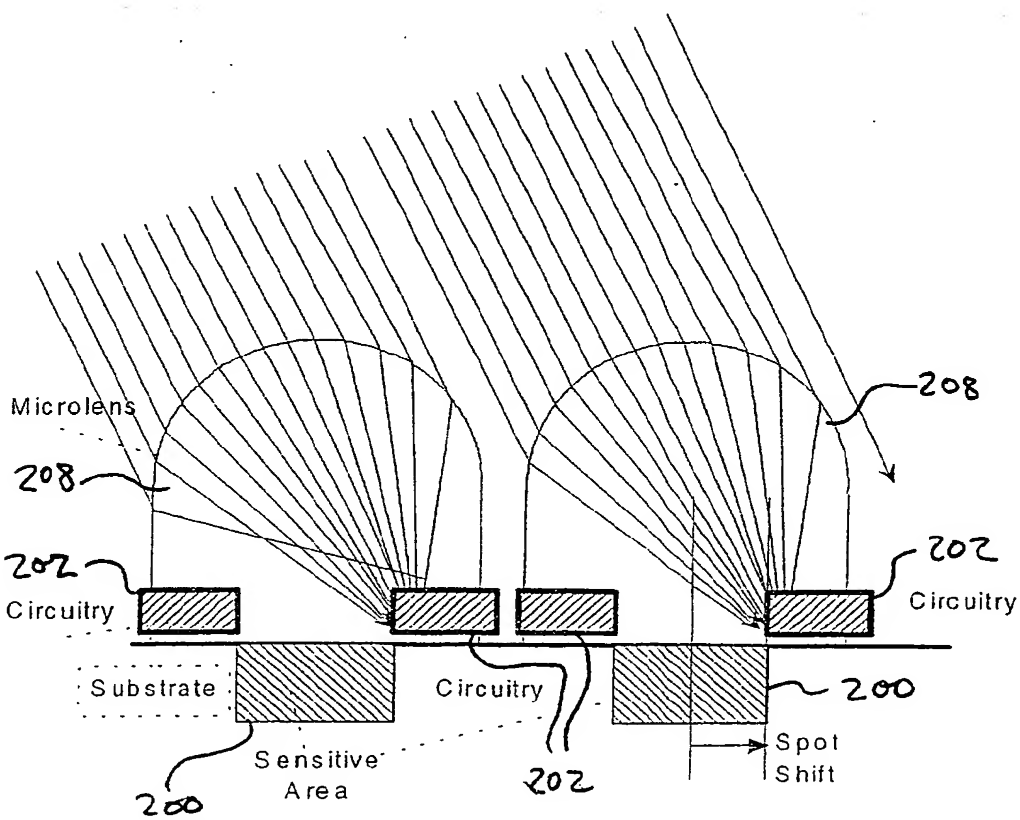

Figure 4 Off-axis illumination with Vignetting

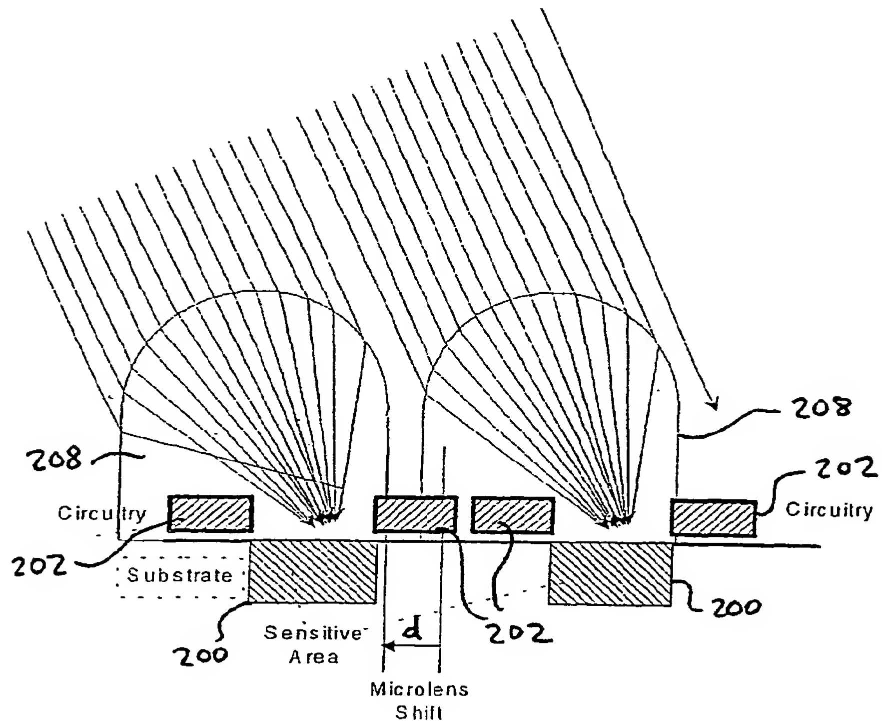

Figure 5 Off-axis illumination with shifted microlens

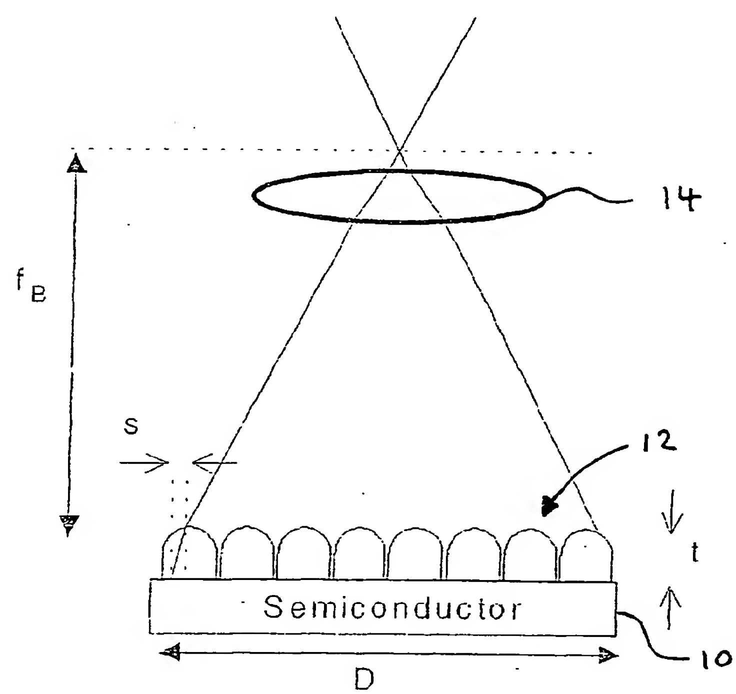

Figure 6 Microlens Shift Approximation

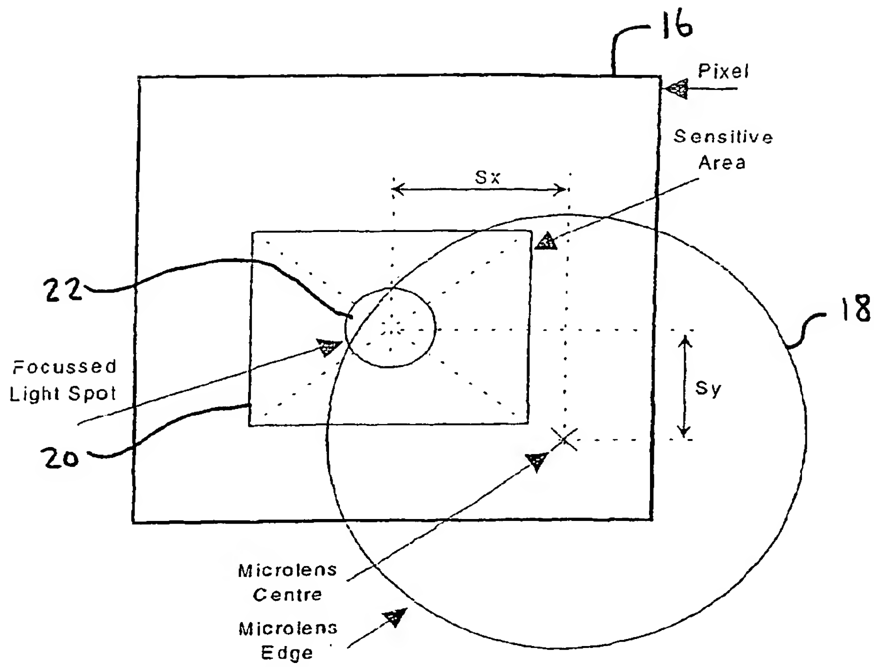

Figure 7 Pixel at Top-Left of array with shifted microlens

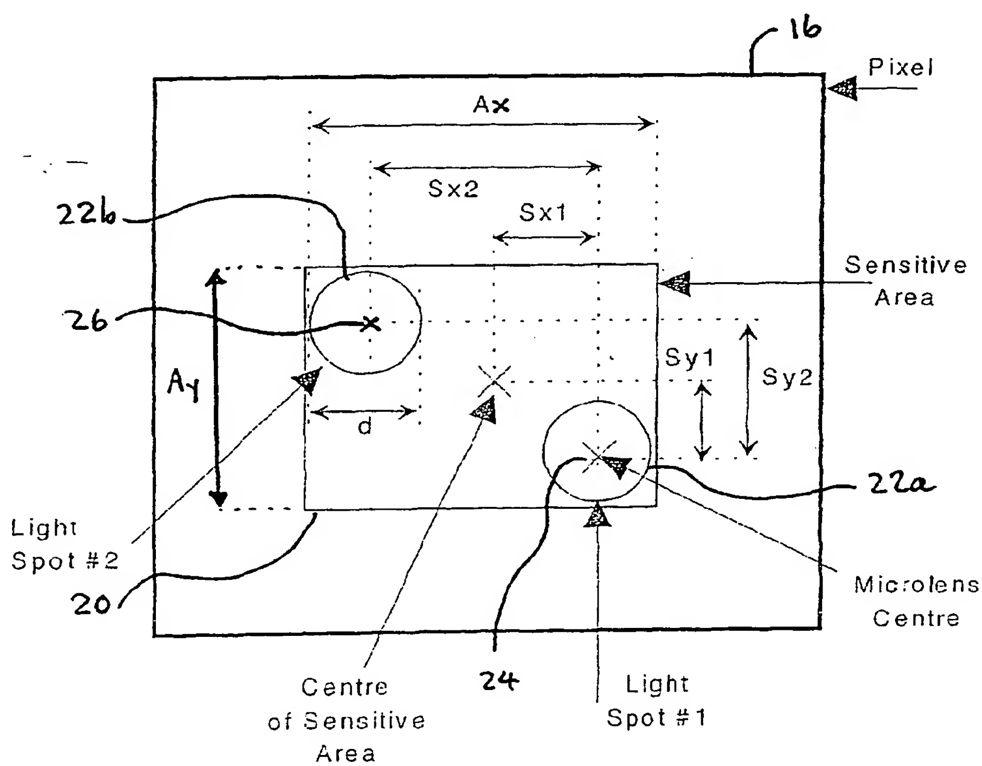

Figure 8 Pixel plan view with different primary lenses

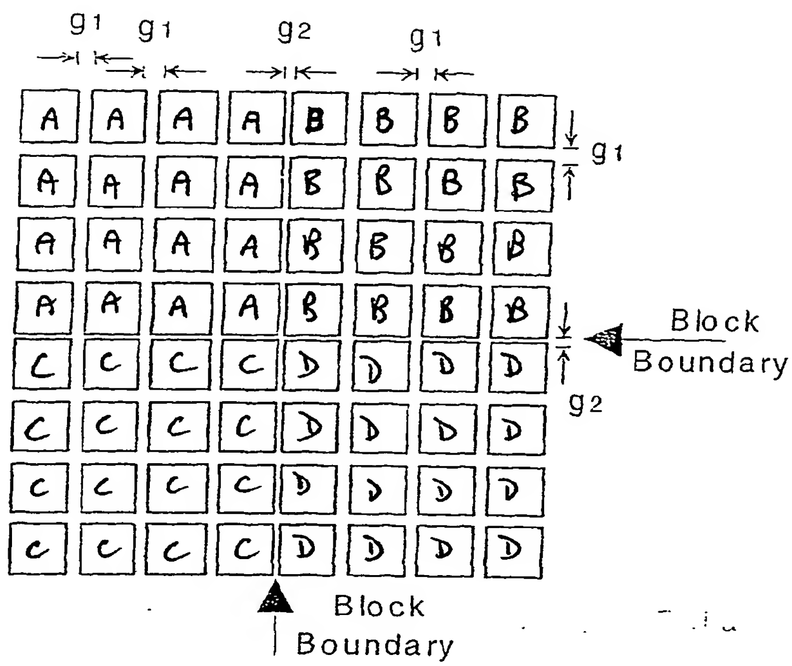

Figure 9 Block shift of microlenses – narrower gaps

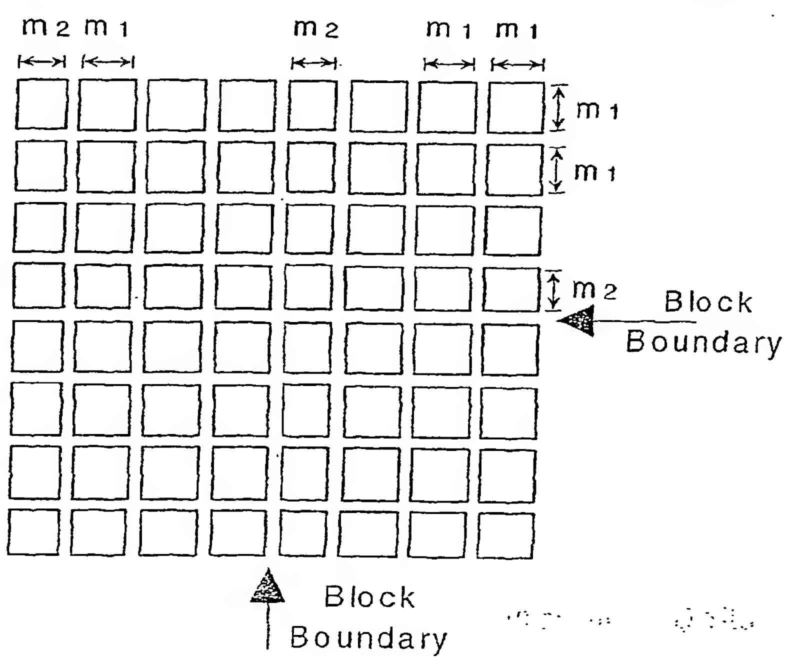

Figure 10 Block shift of microlenses - smaller lenses

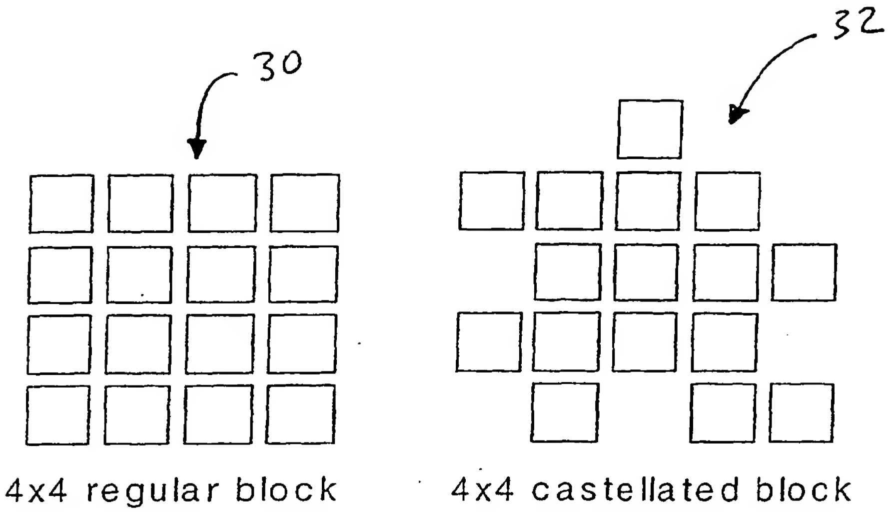

Figure 11 Regular and castellated blocks

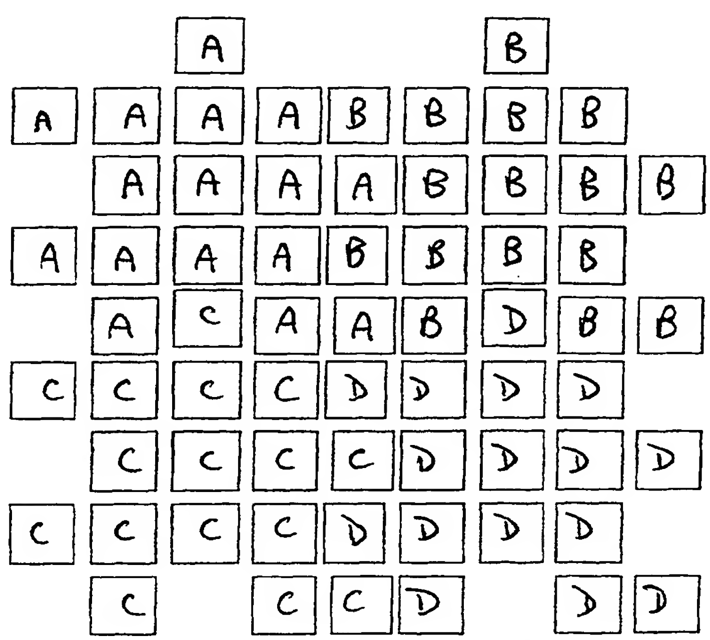

Figure 12 Narrow gaps using castellated blocks

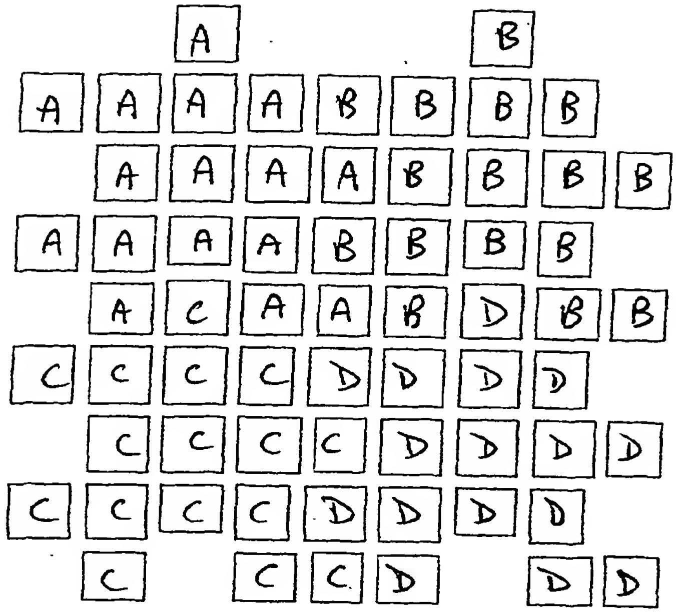

Figure 13 Varying microlens sizes with castellated blocks

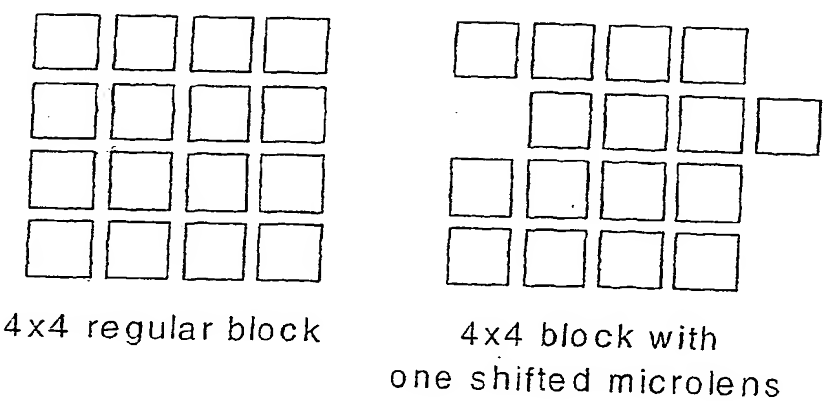

Figure 14 Modified block which tessellates